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CHARACTERIZATION OF SELECTED PROPERTIES FOR ALUMINA-ALUMINUM METAL MATRIX COMPOSITES

SEPTEMBER 1983

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Alumina-Aluminum Metal Matrix Composite Material, known by the trade name Fiber FP/Aluminum and manufactured by E.I. DuPont DeNemours, was evaluated for the following selected properties: Microstructural integrity, tensile strength, fatigue life, charpy impact resistance, and abrasion resistance. The Fiber FP/Aluminum was examined as a possible material alternative for track component application.

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1.0. INTRODUCTION

The widespread use of metal matrix materials has been limited because of fiber costs, manufacturing costs, unrefined fabrication techniques, and the inability to obtain consistent properties due to the reactional interdependence between the matrix and the fiber. There are several ongoing efforts to improve the shortcomings of metal matrix application by looking at alternative fiber and matrix alloys using a variety of fabrication processes.

Fiber FP/Aluminum, an experimental metal matrix material developed by E.I. DePont DeNemours & Co., Inc., is one such composite that shows promise because of its desirable properties. Fiber FP, the trade name given to the fiber, is a continuous, multifilament yarn made of a polycrystalline alpha-alumina. The fiber, as claimed by DuPont, is 98 percent of the theoretical density with a tensile strength of 200 kpsi. The matrix is an aluminum-lithium alloy. The lithium addition to the aluminum (2.5 - 3.5 percent) acts as a wetting agent that improves fiber-matrix bonding. The composite is made using a vacuum infiltration process.

The Metallurgical Laboratory at TACOM purchased test samples of Fiber FP/Aluminum from DuPont for evaluation. The test samples consisted of notched charpy specimens, flat constant area bars for tensile and fatigue testing, and plates for abrasion testing. The samples were made from plates of 35 and 55 fiber volume percentages with fiber orientations of 0°, 90° and $0^{\circ}/90^{\circ}$ cross plies. Impact resistance, ultimate strength, fatigue life, and resistance to wear were the properties of Fiber FP/Aluminum investigated.

2.0. SUMMARY

The objective of this investigation was to evaluate properties of Fiber FP/Aluminum and explore possible application of this experimental composite as an alternate material in vehicle track components. The evaluation parameters used were; microstructural integrity of the material, Charpy impact resistance, ultimate tensile strength, fatigue life, and abrasion resistance.

Microstructural examination of Fiber FP/Aluminum revealed excellent characteristics of the material. Minimul porosity in the composite was observed. The effects of alloying the aluminum matrix with lithium led to a good matrix-fiber bond interface.

The fibers were evenly spaced, with no apparent crossed, misoriented, or broken fibers. The high quality of the wetting characteristics was also indictative of the effectiveness of the vacuum infiltration fabrication process.

The FP/Aluminum demonstrated a high degree of resistance to abrasive wear. Wear values did not deviate significantly between the 35 and 55 fiber volume percentages for the test conducted. Less ceramic in the material was expected to exhibit less abrasive wear resistance.

The Charpy impact resistance of FP/Aluminum appeared to be independant of temperature, a desirable characteristic, but the values were extremely low compared to wrought aluminum.

The tensile strength and fatigue life results were marred by the unanticipated internal fiber damage done by machining a reduced area and by the serrated jaws of the tensile machine. Tensile results illustrate the need for a standard method of tensile testing metal matrix composites to yield results that give a more reliable and reproducible assessment of the material.

3.0. CONCLUSIONS

The results of testing for various properties of Fiber FP leads to the following conclusions:

3.1. The microstructural quality of Fiber FP Aluminum is excellent. There is good fiber-matrix bonding due to the lithium alloying of the matrix. There was a minimal amount of fiber pullout. The fact that a liquid metal infiltration process is used for casting Fiber FP implies that complex shaped parts of high microstructural composite quality could be made.

3.2. Ultimate tensile strength values obtained for Fiber FP samples are in conflict with the manufacturer's reported values probably due to preparation for testing. This illustrates the need for a more standardized means of tensile bar fabrication and testing for composite material to give a more accurate assessment of the material's properties.

3.3. The delicate nature of a ceramic fiber matrix makes the machining of reduced-area tensile bars a fragile and unpredictable operation. The extent of fiber damage done while machining is not readily quantifiable.

3.4. Fatigue limit results for $0^{o}/90^{o}$ 55 v/o should be viewed in light of the undetermined fiber degradation caused by machining. The values obtained show a stabilizing limit approaching 60 percent of the ultimate strength values.

3.5. Due to the low impact resistance of the material, vehicle track applications would be very limited. However, due to the other excellent properties, the selective use of this type of material may be desireable in the future for lightweight, high strength abrasian resistant applications.

3.6. Fiber FP aluminum exhibited very good abrasive wear characteristics. The vitrified abrasion wheels exerted similar wear values for $0^{o}/90^{o}$ for each fiber volume percentage.

4.0. RECOMMENDATIONS

None.

5.0. DISCUSSION

The Fiber FP/Aluminum test samples purchased by DuPont were cut from plate castings with fiber-volume percentages of 35 and 55. Flat tensile bars, notched Charpy impact specimens, and flat abrasion plates were cut so the particular test samples had fiber orientations of 0°, 90°, and $0^{\circ}/90^{\circ}$.

Characteristics of interest for track application that were looked at include:

1. Microstructural integrity
2. Ultimate tensile strength
3. Fatigue limits
4. Charpy impact resistance
5. Abrasion resistance
6. Cost
7. Weight

5.1. Microstructural Properties.

In order to maximize the properties of composite material in general, the porosity of the material must be at a minimum. The matrix must be able to wet the fiber without causing fiber degradation, bunching of the fibers, or misorientating the fibers. Fiber FP/aluminum has excellent fiber-matrix density characteristics. There was minimal fiber degradation and fibers maintained their spacing and orientations. The wetting and infiltration efficiency of the matrix illustrated the effectiveness of lithium alloying of the matrix and the merits of the vacuum infiltration process.

5.2. Tensile Strength.

Tensile strength tests were conducted in samples of 35 and 55 v/o with fiber orientations of 0°, 90°, and 0°/90°. Testing was done on an Instron Model 1333 closed loop, hydraulic testing system.

5.2.1. Composite material tensile testing is not a standardized procedure. Test samples can have reduced areas of various contours with tabs on the ends or samples may have a constant area. The reason for the variation in testing is because different composites act differently under tensile stress. Test specimens that use tabs glued to the ends sometimes give results that don't accurately characterize the tensile strength of the material. This is due, in part, to unequal stress distribution caused by the strain compatibility of the tabs, bonding medium, and sample.

5.2.2. Work done at the Army Materials and Mechanics Research Center (AMMRC) by Oplinger, Gandhi, and Parker (Report No. AMMRC-TR-82-27) "Studies of Tension Test Specimens for Composite Material Testing", proposes that the contour of reduced area tensile bars can be streamlined to relate a more accurate accessment of the material's tensile properties. The report shows that unequal concentrations of shear and tensile stress arise in the reduced area and tab-composite interface that alter the material's true load bearing characteristics, thereby giving an unreliable tensile strength value. Stress analysis done by AMMRC showed that a streamlined taper lowered the shear and tensile stress concentrations inherant in tensile testing of composite materials. This work was done on glass reinforced material but it was felt that the streamline design theory could be transposed to metal matrix samples as well.

5.2.3. In light of the AMMRC work done on stress analysis of glass composites and with the desire to use an expeditious method of obtaining reliable tensile results, a reduced area, streamline design was used for the Fiber FP tensile bars. The dimensions of the tensile bars were 6 inches X 1/2 inch X 1/10 inch, similar to a dogbone design, but with a streamlined radius. Machining was done with a fine grit, water cooled surface grinder. Figure 1 illustrates the streamline tensile bar configuration.

5.2.4. We felt that the minimum force required to grip the samples with the serrated jaws of the tensile machine would be such that the fiber integrity would not be altered. This did not prove to be the case, however, as average stress results ranged from 20 - 50 ksi, values 50 percent lower than DuPont's claims. Inspection of the tensile bar ends revealed significant fiber damage on some of the bars. Figure 2 shows a tensile bar with the most severe case of tensile bar grip penetration.

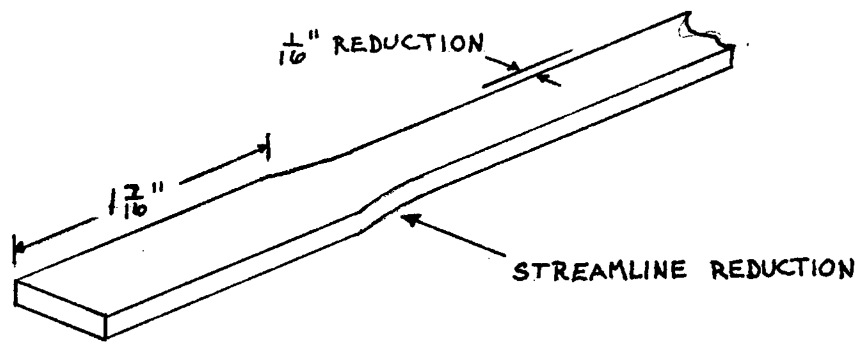


Figure 1 - Illustration of Streamline, Reduced Area Tensile Bar

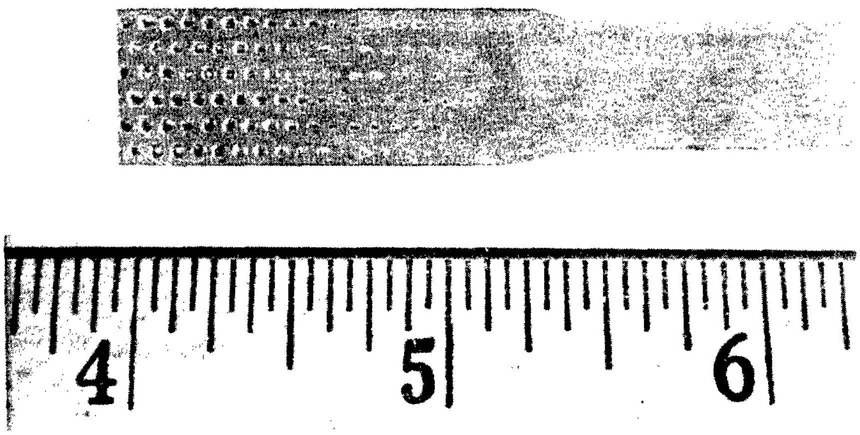


Figure 2 - Tensile Bar Illustrating Damage Caused by Tensile Bar Grip Penetration

Microscopic measurement of the surface damage caused by the serrated jaws showed that, in the worst case, indentations averaged 1/64 inch deep and 2/64 inch wide to form a diamond-shape impression. The effects that the indentations had on the ultimate strength can only be estimated, not determined. Considering a jaw penetration depth of 1/64 inch with six rows of serrations on both sides of the bars, approximately 10 percent of the cross sectional area was directly affected. The fact that each tensile bar broke in the midsection of the reduced area leads to the conclusion that the streamline design may be a viable means of tensile test design. The damage on the sample done by the serrated jaw shows a 10 percent reduction in the effective cross-sectional area. These yields, however, are well below DuPont's reported values. The only other explanation for the low tensile strength values is that damage was done to the fiber integrity while machining the reduced area. One theory is that due to the vibratory effects of the surface grinder, significant internal fiber damage occurred. The brittle nature of the alumina could lead to broken or severely flawed fibers. This would seem to have a more acute effect on cross-ply composites ($0^{o}/90^{o}$).

5.2.6. Table I compares the relative stress results obtained in tensile testing. The cross-sectional area used to calculate the stress does not take into account the 10 percent area loss due to the serrated jaws of the tensile machine or the fiber degradation that may have occurred due to machining the reduced area.

Fiber Volume Percentage	Fiber Orientation	Ultimate Load (pounds)	Stress (ksi) (ksi)
55	0 °/90 °	1437.5	35.05
		1437.5	35.05
		2112.5	51.50
	0 °	2125	51.80
		2125	51.80
		2125	51.80
	90 °	1187.5	28.90
		1312.5	32.00
		1281.25	31.20
35	0 °/90 °	1687.5	41.10
		1875	45.70
		1750	42.60
	0 °	2125	51.80
		2125	51.80
		2125	51.80
	90 °	937.5	22.90
		1050	25.60
		1000	24.40

Table 1 - Relative Tensile Strength of Fiber FP/Aluminum

5.3. Fatigue Life.

Fatigue testing was carried out on a sample set with a fiber/volume percentage of 55 and an orientation of 0 $^{\circ}$/90 $^{\circ}$ at a temperature of 70F $\pm$ 5F. This particular volume and orientation was chosen because any possible track application would require the desirable wear characteristics inherant in having more ceramic in the material and multidirectional loading strength.

A uniaxial load was applied with a stress ratio of 0 at a frequency of 1 Hz. The resulting curve, shown in Figure 3, was produced by a linear regression program interfaced with a Hewlett-Packard Series 9800 plotter pac. The values used in the curve do not consider the fiber damage as noted in the previous section. Scanning Electron Microscope (SEM) analysis of the fracture face showed virtually no fiber pullout. Figure 4 is a representative fracture face photograph showing the extent of fiber pullout.

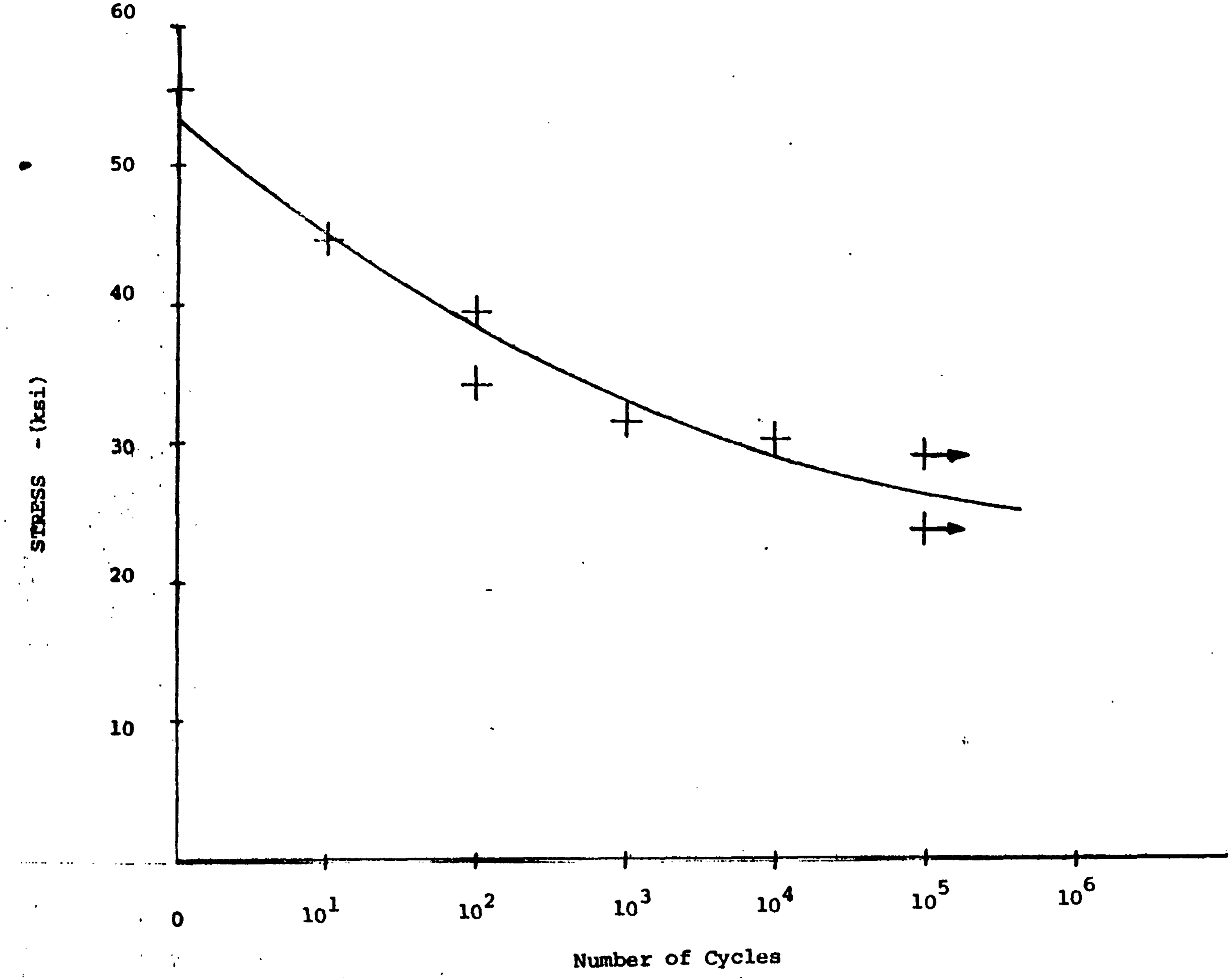


Figure 3 - S-N CURVE OF $0^o/90^o$, 55v/o FIBER FP

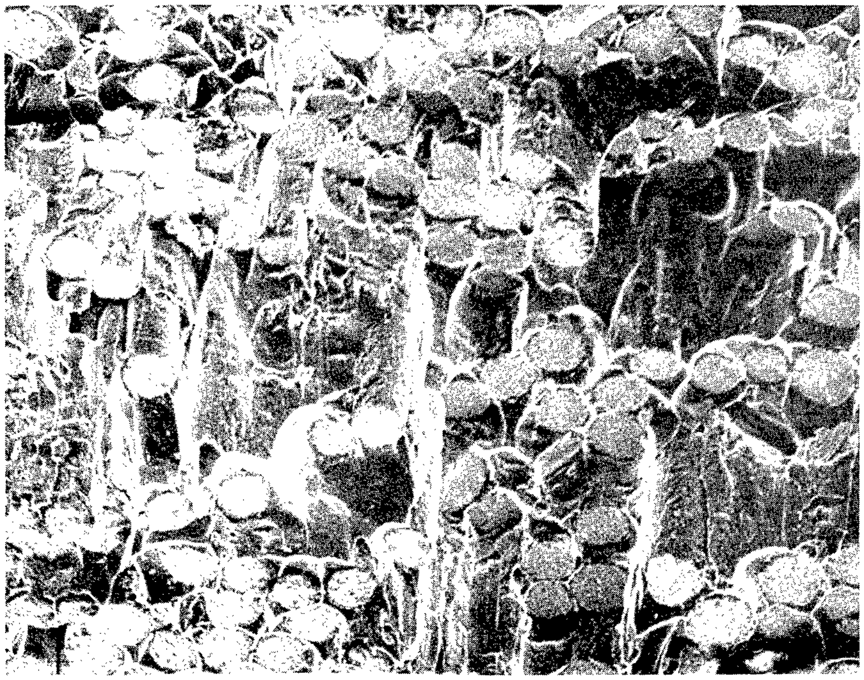


Figure 4 - Microphotograph of Representative Fatigue Sample Fracture Face (400X)

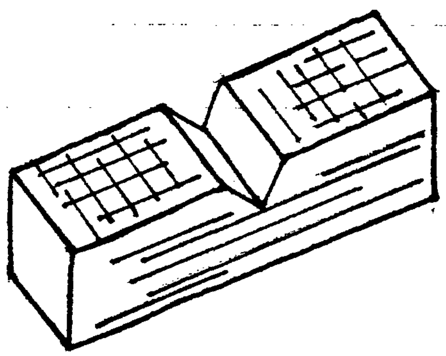
5.4. Impact Resistance.

5.4.1. Charpy samples were supplied with 35 and 55 fiber/volume percentages. Within these two groups, there were fiber orientations of 0 °/90 °, 0 ° or 90 °, with notch orientation parallel or perpendicular to the fiber lamina. Figure 5 illustrates the notch orientations.

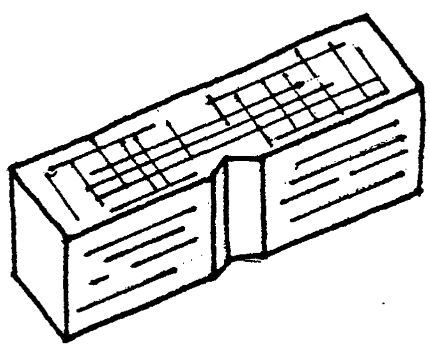
5.4.2. Test samples were run in temperatures ranging from -60F to 212F. Below-freezing samples were maintained at their respective ranges by immersion in an alcohol bath for no less than five minutes.

5.4.3. Table 2 summarizes the results of the Charpy impact tests. As can be seen from the table summary, there is no discernable impact resistance associated with fiber/volume percentages or the notch orientations. The results show no discernible pattern between the impact resistance and the temperature probably due to the low sensitivity of the Charpy impact machine used.

5.4.4. SEM photographs of Charpy fracture faces show the effectiveness of the matrix wetting characteristics. Figure 6 shows the distinct matrix-fiber reaction zone. The exact reaction occurring, as noted by DuPont, is not fully understood and it is not in the scope of this evaluation to determine the alumina aluminum-lithium reaction. Figure 7 shows the failure mode for all temperature ranges and fiber orientations. There is a matrix-fiber reaction zone surrounding the fiber and failure occurred within the matrix and not as a result of unfavorable wetting characteristics. SEM observation of the fracture faces shows a notable reduction in the number of sheared fibers as the temperature is reduced.



notch parallel to plies
of $0^{o}/90^{o}$ orientation



notch perpendicular to plies
of $0^{o}/90^{o}$ orientation

Figure 5

Example of Charpy Specimen
Notch-Fiber Orientation

PLATE CAST NUMBER	FIBER-VOLUME PERCENTAGE	FIBER ORIENTATION	NOTCH-FIBER ORIENTATION	TEMPERATURE				
				$-60^{\circ}F$	$-40^{\circ}F$	$0^{\circ}F$	$70^{\circ}F$	$212^{\circ}F$
138DJ-29	35	$0^{\circ}/90^{\circ}$	⊥	.5,.5, 1,.75	1,1, .5,.75	.75,.5, .75,.75	1,1, .5,.75	1,1, 1,1
			‖	1,1, 2,1.5	1,1, 1.5,2	1,1, 1.75,1	1.25,1.5, 1,1.5	1.5,2, 1.25,1.75
138DJ-66/68	35	90°	⊥	.5,.5, .75,.75	.5,.5, .5,1	1.5,.5, 1.25,1.5	1,1, 1,1	1,1.5, 1,1
			‖	1,1, 1,1	1,1, 1,1	1.75,1.25, 1.25,1.75	2.5,2, 2,2	2,2.5, 3,2.5
138DJ-48	55	$0^{\circ}/90^{\circ}$	⊥	1,.5, .5,.5	.5,.5, .5,1	1,.75, .5,.75	1,1, .5,1	1,1, 1.25,1
			‖	1,1, 1,1	1,1, 1,1	1.25,1.25, 1.5,1.5	1.25,1.5, 1.5,1.25	1.5,1.5, 1.75,1.25
138DJ-15/19 /21/22	55	90°	⊥	.5,.5, .5,.5	1,.5, .5,1	.5,.5, .5,.5	.5,.5, .75,.75	.5,.5, 1,1
			‖	.5,.5, .75,.5	1,.5, .5,1	1,1, 1,1	.75,.5, 1,.5	1.5,1.75, 1.5,1.5
138DJ-37	35	0°	⊥	1,1, .5,1	.5,.5, 1,.5	.5,.5, .5,1.5	.5,.75, .5,.5	1,1, .5,.75
138DJ-6	55	0°	⊥	.5,.75, .5,.5	.5,.5, .5,.5	.5,.5, .5,.25	.5,.5, .5,.5	.75,.5, .5,.5

Table 2 - Charpy Impact Test Results (values in ft-lbs.)

Figure 6 - Matrix-Fiber Reaction Zone (2200X)

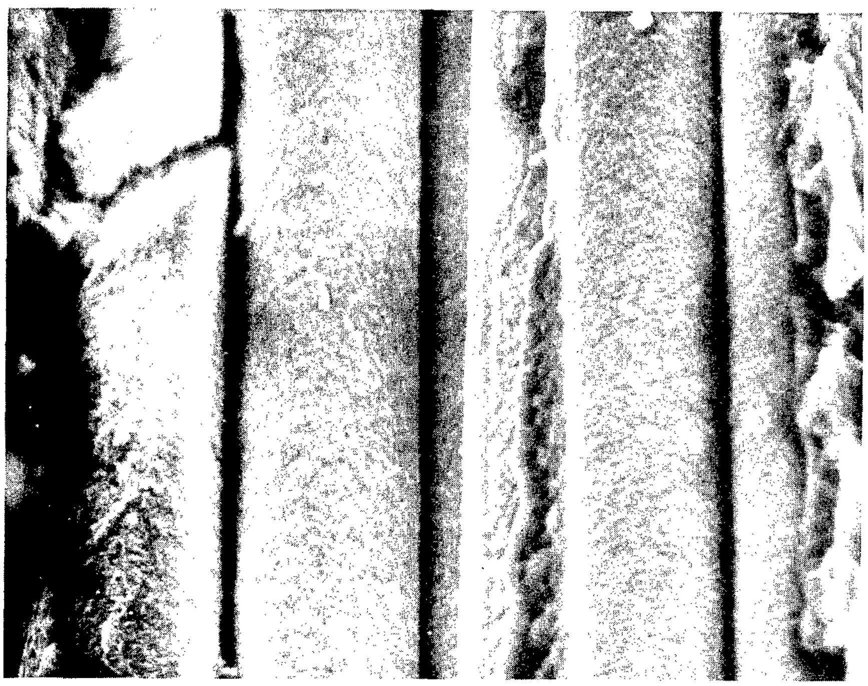


Figure 7 - Matrix Failure (1100X)

5.5. Abrasion Resistance.

5.5.1. Abrasion resistance of the Fiber FP was determined by using 4 inch X 4 inch X 1/2 inch samples on a Taber Model 503 Abraser.

5.5.2. The Taber Abraser allows for a constant load to be applied on the abrasive-test material interface as the test material rotates. A load of 1000 grams was maintained for each test. Each sample was run for 10,000 cycles using either an H-10 grit abrasive wheel or a coarser, H-22 grit wheel.

5.5.3. A weight loss method of the relative abrasion resistance was used, called the Taber Wear Index. This method is based on the weight loss of the test sample in milligrams per throusand cycles. Table 3 compares the relative abrasion resistance between samples tested.

5.5.4. Using the H-10 grit abrasive wheels, there is no distinction between the wear characteristics of 35 or 55 fiber/volume percentages. Each was highly resistive to abrasion. The H-22 grit abrasive wheels generally had a higher effect on the Fiber FP, but more $0^{\circ}/90^{\circ}$ sample tests would be required on the H-22 wheels in order to obtain a reasonable standard deviation and a more accurate assessment of the material's wear index. The limited number of abrasion test panels purchased did not allow this.

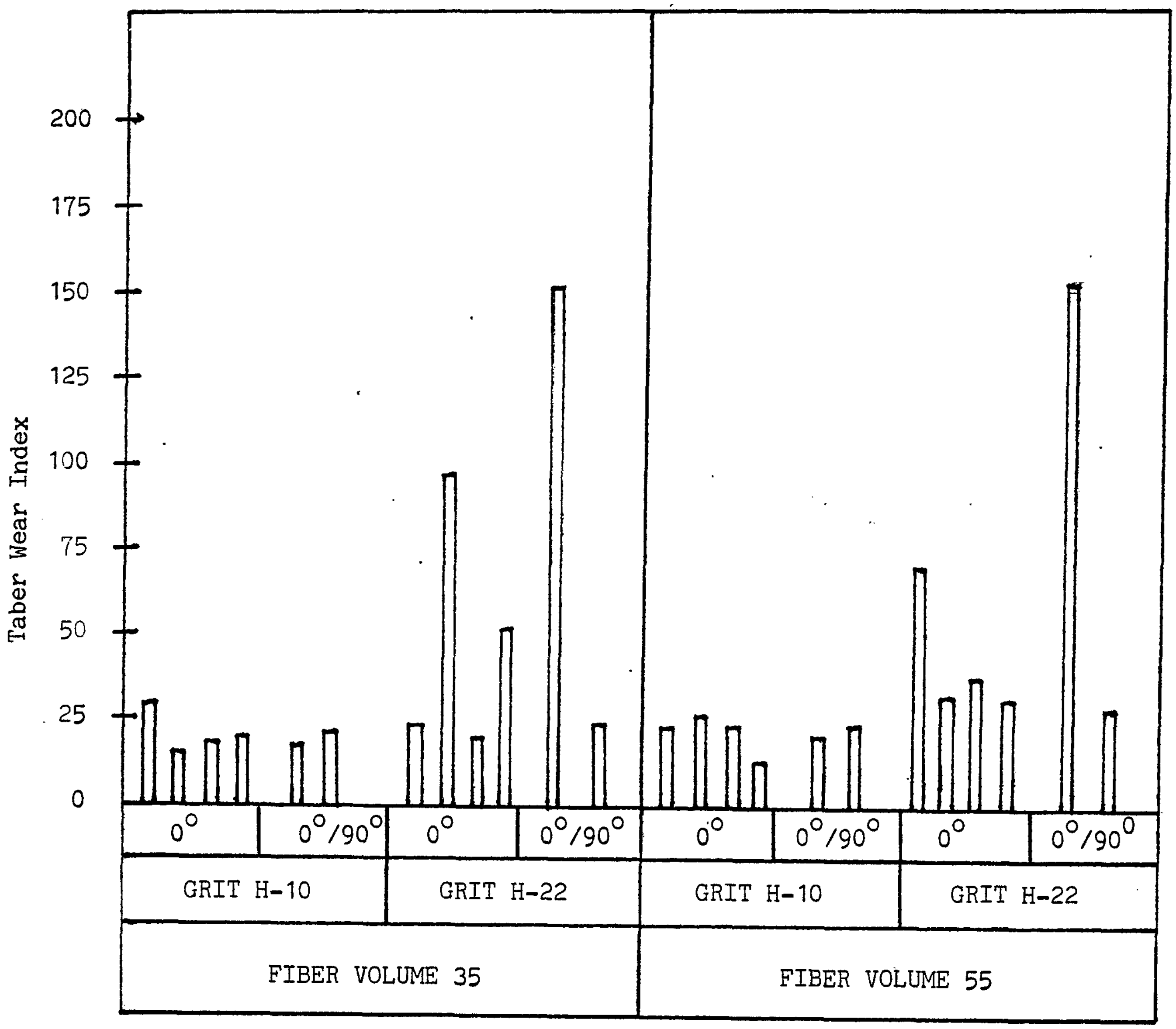


Table 3 - Relative Abrasion Resistance of FP/Aluminum

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